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STABILITY AND CONTROL CHARACTERISTICS OF A MODEL OF AN AERIAL VEHICLE SUPPORTED BY FOUR DUCTED FANS

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SUMMARY

The stability and control characteristics of a simple, lightly loaded model approximately one-third the size of a full-scale vehicle have been investigated by a series of free-flight tests. The model is representative of a type of vertically rising aircraft which would utilize four ducted fans as its sole source of lift and propulsion. The ducts were arranged in a rectangular pattern and were fixed to the airframe so that their axes of revolution were vertical for hovering flight. Control moments were provided by remotely controlled compressed-air jets at the sides and ends of the model.

In hovering, the model in its original configuration exhibited divergent oscillations about both the roll and pitch axes. Because these oscillations were of a rather short period, the model was very difficult to control by the use of remote controls only. The model could be completely stabilized by the addition of a sufficient amount of artificial damping. The pitching oscillation was made easier to control by increasing the distance between the forward and rearward pairs of ducts.

In forward flight, with the model in its original configuration, the top speed was limited by the development of an uncontrollable pitch-up. Large forward tilt angles were required for trim at the highest speeds attained. With the model rotated so that the shorter axis became the longitudinal axis, the pitch trim problem was found to be less than with the longer axis as the longitudinal axis. The installation of a system of vanes in the slipstream of the forward ducts reduced the tilt angle but increased the power required.

INTRODUCTION

There has recently been much interest in the development of a simple, inexpensive, easily operated vertical-take-off-and-landing (VTOL) vehicle for aerial reconnaissance and light transport missions.

Some of the operating characteristics desired for the vehicle include hovering capability, forward speeds up to about 50 knots, a payload of about 1,000 pounds, and the ability to operate at very low altitudes in the so-called "nap of the earth." The opinion appeared to be widely shared that a vehicle having the desired characteristics would be one incorporating some arrangement of multiple ducted fans as the main source of lift and propulsion. Although some information has been available on the basic characteristics of ducted fans as the main source of lift and propulsion, the areas of application in which ducted fans might be utilized in groups have until recently remained largely unexplored. To provide information on the stability and control characteristics of multiple-duct vehicles, the National Aeronautics and Space Administration undertook a program of force tests and flight tests on small-scale models generally representative of the more promising configurations suggested by manufacturers. This paper presents the results of a series of free-flight tests performed on a model of a four-duct configuration. Reference 1 presents a general discussion, based in part on some of these tests, of some of the stability and control problems to be anticipated with a vehicle depending on fixed ducted fans for its lift and propulsion.

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MODEL

The model, shown in figures 1 and 2, was not meant to represent any particular full-scale machine; rather, it was intended to be simply a research vehicle which might yield information generally applicable to a number of four-duct configurations. For purposes of discussion in this paper, the model will be considered as being one-third the size of a full-scale vehicle.

The ducts, of sheet aluminum construction with spun aluminum inlet lips, were arranged in a rectangular pattern on an aluminum and plywood frame. Near the exit of each duct was a fan which had four wooden blades of 3-inch chord and 7-inch radius. These blades were set at a blade angle, measured at the 0.75 radius station, of 34°. Clearance between blade tip and duct wall was approximately one-eighth inch. Power was supplied to the fans by four pneumatic motors, one located in each duct. These motors were driven by a common source of compressed air but were not otherwise interconnected.

The arrangement of the ducts on the airframe shown in figure 1(a) was such that the model in its original configuration had the same over-all width and "cargo space" (the space in the center of the model between the forward and rearward duct lips) as the two-duct model of references 2 and 3. Aluminum structural members were provided to permit the longitudinal distance between the forward and rearward pairs of fans to be altered to produce two configurations other than the original as shown in figure 1(b). In the first of these altered configurations, the longitudinal distance between the centers of the forward and rearward pairs of fans was made the same as the distance between fan centers on the previously mentioned two-duct model which had fans of 14-inch radius. The second altered configuration was one in which the overall length of the four-duct model equalled the overall length of the two-duct model. For all of the configurations, the overall model width and lateral placement of the fans remained constant.

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During some of the forward-flight tests, a cascade of vanes was installed in the slipstream of the forward pair of ducts. A drawing of the model with these vanes installed is presented as figure 1(c). The vanes had a chord of 3 inches, and were hinged along their midchord line so that both the deflection and camber could be varied. These vanes were the same ones which were installed in the two-duct model for the force tests of reference 2.

For all tests, model control and trim moments were provided by small compressed-air jets located at the sides and ends of the model. Some of these jet-reaction controls were operated by the pilots who controlled them remotely through the use of flicker-type (full-on or full-off) electropneumatic actuators. The actuators were equipped with integrating trimmers which trimmed the control a small amount in the direction the control was moved each time a control deflection was applied. With actuators of this type, a model becomes accurately trimmed after flying a short time in a given flight condition. These remotely controlled jets provided moments of about 13.5 foot-pounds (18.5 and 22.0 foot-pounds for the two longer configurations) in pitch, 7.0 foot-pounds in roll, and 7.5 foot-pounds in yaw. Other jet controls were employed at times to produce artificial damping for the model. In this application, the jet controls were actuated by proportional pneumatic servos which moved in response to signals from gyroscopic devices sensitive to angular velocities.

The mass characteristics of the model varied somewhat from one phase of testing to another, as control mechanisms, vanes, ballast weights, and so forth, were added or removed, but the following values are believed to be reasonably representative of average values for the model in its original configuration without the turning vanes:

Weight, lb	60
Moment of inertia about roll axis, slug-ft^2	1.2
Moment of inertia about pitch axis, slug-ft^2	3.5
Moment of inertia about yaw axis, slug-ft^2	3.9

No determinations were made of the moments of inertia in the elongated configurations or with the slipstream vanes installed. The weight of the vane assembly, however, was about 14 pounds.

TEST SETUP AND PROCEDURE

Hovering Flight

The hovering tests were performed in an enclosed test area about 70 feet square and 50 feet high which provided protection from random disturbances due to wind. Some slipstream recirculation developed in this area during flights, but it did not seem to have any great effect on the behavior of the model. The setup was generally similar to the one shown in figure 3, although for the hovering tests the model was not installed in a wind tunnel.

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The model was equipped with a steel safety cable, by means of which crashes could be avoided in the event that normal control of the model was lost. This cable ran from an attachment point just above the center of gravity of the model, through a pulley fixed to the building structure about 40 feet above the floor, then down to a safety-cable operator stationed on the floor. A flight cable, made up of light electric cables and flexible plastic tubes, was used to conduct remote control signals and compressed air to the model during flight. The flight cable was attached to the model near the center of gravity and was fastened along the steel safety cable up to a point about 15 feet from the model. At that point it left the safety cable and ran approximately horizontally out to the supply connections for the electrical signals and the compressed air.

The electrical control signals originated at control boxes which were operated by pilots stationed on the floor of the flight area. Although it is in some cases possible for one man to control the model about all three axes simultaneously, the usual test technique is to assign separate pilots to the roll, pitch, and yaw controls. Through this division of pilot duties, each man is able to study in detail that particular phase of the model behavior with which he is directly concerned. A fourth man operated the throttle valve which controlled the supply of compressed air to the fan motors in such a manner as to maintain approximately the desired altitude for flight.

The general procedure for the hovering tests might best be illustrated by the description of a typical flight. Tests usually began with the model suspended in the air by the safety cable. The power operator then opened the throttle valve and the three pilots applied appropriate

controls when the safety cable became slack and the model attained a trimmed hovering condition at an altitude of about 15 feet above the floor. Certain experiments with the controls were performed, depending upon the nature of the investigation, and the response of the model was noted. Normally, the motions about only one axis at a time were subject to experimentation; motions about the other two axes were restricted to a minimum by the pilots having direct control about those axes. In some cases, artificial stabilization was employed to aid in further minimizing these extraneous motions. At the conclusion of a flight, power was reduced and the weight of the model was again taken by the safety cable.
L During the take-off-and-landing tests, the model started from a condition
1 of rest on the floor with the safety cable slack. Power was applied until
4 the model had risen to an altitude of about 10 feet; this altitude was
8 held constant for a brief period of steady hovering flight. The power
2 was then adjusted for descent and was cut off abruptly as the model touched
the floor.

Forward Flight

The forward-flight tests were performed in the test section of the Langley full-scale tunnel. A drawing of the setup similar to that used for these tests is presented as figure 3. The basic model and the method of controlling it were the same as those for the hovering tests.

A forward-flight test usually began with the model suspended by the safety cable in the test section of the tunnel. The tunnel was then started; and after a predetermined airspeed had been reached, power was applied to the model and the power operator and the three pilots operated their controls in an effort to set up and maintain a trimmed forward-flight condition with the safety cable slack. At the end of a test flight the model power was shut off and the model again became supported by the safety cable.

RESULTS AND DISCUSSION

In attempting to interpret results of free-flight model tests, it must be remembered that the behavior of a model, remotely controlled by human pilots, is not necessarily an exact representation of the behavior of a full-scale machine. Certain scale effects exist which usually cause the model tests to yield results which appear somewhat pessimistic when compared with actual flight results. Among these effects, and of particular importance to the tests discussed in this paper, is the time lag between the requirement for a control and its actual application. In contrast with the pilot of a full-scale machine, who can sense accelerations kinesthetically and apply corrective controls without waiting for a displacement to develop, the model pilot usually applies controls only in response to an observed displacement. A time lag is, therefore, introduced into the model pilot's response; and when it is considered that model angular motions are inherently more rapid than those of a full-scale machine, it is seen that the phase lag between the need for a control and its actual application may be appreciably larger for the model than for the full-scale machine and that the model flight may be somewhat rougher than that of the full-scale machine.

A motion-picture film supplement has been prepared and is available on loan. A request card form and a description of the film will be found at the back of this paper, on the page immediately preceding the abstract pages.

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Hovering Flight

For purposes of discussion in the investigation of hovering flight, the longer horizontal axis of the model will be considered as the longitudinal axis.

Possibly the most outstanding dynamic stability characteristics of the model in hovering flight were unstable oscillations in both pitch and roll. This instability had a powerful effect on the flight behavior and seems inherent in many ducted-fan configurations since the source of the exciting force seems to lie in the response of the aerodynamic forces on the duct and fan to changes in translational velocity and angle of attack. Quantitative data on these forces were obtained for a two-duct model and are reported in reference 2. Because of similarities in configuration and because the dynamic stability characteristics of the four-duct model were generally quite similar to those of the two-duct model, it was assumed that the force and moment characteristics of the two models would be generally similar and the results of the four-duct-model tests would be explainable on the basis of force and moment characteristics such as those measured for the two-duct model. By correlating force-test information with the observed flight behavior, the following qualitative analysis of the mechanics of an oscillation in roll will be considered although the general argument may apply equally well to an oscillation in pitch. If the model, initially in a trimmed hovering condition, encounters some disturbance which produces an angular displacement about the roll axis, the resultant thrust vector is displaced from the vertical to some new attitude in which it has a horizontal component in the direction toward which the model was rolled. If the initial roll displacement is considered to be toward the right, the model is then accelerated to the right. As the velocity to the right increases, aerodynamic forces develop which produce a rolling moment to the left in the direction to restore hovering equilibrium. With the explanation taken only this far, the motion would appear to be stable. However, the damping in roll is too small in proportion to the static restoring moment (rolling moment due to sideslip), and so the model overshoots the level attitude required for hovering equilibrium and attains an attitude in which the roll angle to the left is even greater than was the initial angle to the right. The lateral forces are then heavily out of balance toward the left, and the model enters the second half-cycle of a rapidly divergent oscillation.

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<u>Longitudinal characteristics</u>.- The model, in its original configuration, was considered very difficult to control in pitch. The inherent oscillation was rapidly divergent and of such a short period (approximately 3 seconds) that prolonged flights required a great deal of pilot skill and attention. There is the possibility that part of the difficulty of control might be attributed to the lack of mechanical interconnection between the model fans. Although it is unlikely that this lack of interconnection would have contributed appreciably to the period of the oscillation or to its divergent nature, it might have given rise to random differential changes in thrust which would have initiated the oscillation by creating angular disturbances in pitch.

The model could be made dynamically stable by the addition of artificial damping about the pitch axis. Artificial damping of approximately 0.9 foot-pound per degree per second of pitching velocity was found to be the minimum required to produce stability. With damping equal to or in excess of this minimum, the model would fly very smoothly for long periods of time without the need for pilot control, other than that occasionally necessary to restrain a slow, random, wandering motion. The wandering may have been due to the differential changes in fan thrust previously mentioned, or to the recirculation of the model slipstream in the enclosed test area.

Increasing the longitudinal distance between the forward and rearward pairs of fans resulted in a significant change in the pitch characteristics of the model. When the model was elongated to an overall length of 68 inches (in which configuration the distance between the axes of rotation of the forward and rearward fans was 50 inches, the same as for the two-duct model of refs. 2 and 3), the period of the uncontrolled pitching oscillation increased to approximately 5 seconds, the rate of divergence in terms of time was reduced, and the horizontal displacements became larger in proportion to the pitch angles than for the original configuration. The increased period and decreased rate of divergence had highly beneficial effects on the ease with which the model could be controlled in pitch. The second elongated configuration, in which the overall length was 86 inches (the same as for the two-duct model), was even easier to fly than was the 68-inch configuration. With a period of approximately 6 seconds, the uncontrolled pitching oscillation of the 86-inch model resembled that of the 68-inch model in that the rate of divergence was lower and the horizontal displacements greater in proportion to the pitch angles than for the original configuration. Time histories of typical uncontrolled pitch oscillations, taken from the motion-picture records of flight tests, are presented in figure 4 for the three model lengths.

Both of the elongated configurations could be flown smoothly for long periods of time without the aid of artificial damping in pitch and without imposing any great demands on the pilot's skill and attention. Because it was believed that the changes in model length would have little, if any, effect on the roll characteristics, the investigation of the behavior in roll was limited to the original configuration.

Lateral characteristics.- The model was very difficult to control in roll without the addition of artificial damping. Flights were possible with no artificial damping, but even a highly skilled pilot was frequently unsuccessful in preventing the development of an oscillation which quickly reached sufficient amplitudes to force the termination of the flight. Because of the previously discussed effects inherent in the model tests, these flight results may, however, be regarded as being somewhat pessimistic; so it is within reason to expect that a full-scale machine would not be as difficult to control. The uncontrolled oscillation had a period of about 2 seconds, and was rapidly divergent. Time histories of a typical uncontrolled rolling oscillation are presented in figure 5.

The rolling oscillation could be completely stabilized by the addition of artificial damping. It was found that artificial damping of about 0.6 foot-pound per degree per second of rolling velocity was the minimum required for complete stability. With artificial damping equal to or in excess of that value, prolonged flights could be made with only the occasional need for pilot control.

No difficulty was experienced in controlling the model in yaw. The model was neutrally stable about the yaw axis, and could be controlled easily without any need for artificial stabilization.

Take-offs and landings.- Because of the dangers inherent in the operation of an unstable aircraft near the ground, all take-off and landing tests were performed with high values of artificial damping in pitch and roll. With this aid, take-offs and landings could be made easily. Changes, if any, in the stability characteristics due to operation near the ground were masked by the artificial damping, but the effect of ground proximity on power required was noticeable. There seemed to exist a ground-effect cushion, about a foot thick, in which the model possessed altitude stability. This cushion effect seemed to be due to a region of increased static pressure caused by streamlines from the four ducts converging under the central area of the model.

Forward Flight

Previous test experience on the two-duct model, as reported in references 2 and 3, showed that the predominant problems in forward flight for this general type of aircraft could be more properly termed trim problems than stability problems. The forward-flight part of the investigation was, therefore, limited to a study of the longitudinal-trim characteristics of the model, and all tests were made with both the pitch and roll dampers operating - a procedure which obscured the inherent stability characteristics of the model. The longitudinal-trim problem, brought out by references 2 and 3, consisted of two parts: (1) the excessive nose-down tilt angles required for drag equilibrium at any appreciable forward speed, and (2) the large nose-down pitching moments required of the controls to trim the model in forward flight.

The problem of reducing the tilt angle in forward flight is complicated by the fact that as tilt angle decreases at a given forward speed the requirement for nose-down control moment increases. A possible solution seemed to lie in a system of vanes installed in the slipstream of the forward pair of ducts and deflected to produce a force having forward and downward components. With the vanes shown in figure 1(c) installed and appropriately deflected, and with the longer axis of the model as the longitudinal axis, a level model attitude was maintained at forward speeds up to approximately 17 knots (full scale). No pitch-trim difficulties were noted at this speed. No higher speed was attained, however, because the vane deflection required to maintain a level model attitude at higher speeds caused such large losses in lift that the model could not support itself even with the application of full available power. The effect of the vanes on the tilt angle was seen when, for purposes of comparison, flights were made with the vanes removed. In this configuration, it was found that a nose-down tilt angle of 12° was required for trim at a speed corresponding to 17 knots (full scale).

A maximum speed of about 45 knots (full scale, tilt angle of 25°) was attained with the vanes removed, and in this case the condition limiting the speed was the nose-up pitching moment. This pitching moment was a function of the forward speed and became powerful enough at 45 knots (full scale) to cause the model to pitch up against a full nose-down control moment of about 19 foot-pounds. Because the model had an instability of pitching moment with angle of attack, once the pitch-up had begun against full nose-down control, there was no possibility of preventing a continuing decrease in tilt angle. The decreasing tilt angle caused a reduction in trim speed, so that the model decelerated with respect to the tunnel airstream and was blown downwind to the limits imposed by the scope of the safety cable.

The hovering tests of this model had shown clearly the desirability of some form of stability augmentation. Because the forward-flight tests were to be concerned primarily with longitudinal trim problems, it was believed that the tests could be performed more easily and that the value of the results would not be impaired by the addition of artificial damping about the pitch and roll axes. For the forward-flight tests, both with and without vanes, in which the longer model axis was the longitudinal axis, artificial damping of approximately 1.7 foot-pounds per degree per second of pitching velocity was added. In roll, the artificial damping amounted to approximately 4.0 foot-pounds per degree per second of rolling velocity. No artificial damping was applied to the yaw axis in any configuration.

Forward-flight tests were also conducted with the model rotated so that the shorter axis was the longitudinal axis. Maximum speeds of about 38 knots (full-scale, corresponding, tilt angle of 24°) were attained in this configuration. As in the case of the previously discussed vane tests, the top speed was limited by the power available. The pitch-trim problem, which had limited the speeds attained when the model was flown (without vanes) with its longer axis fore and aft, was considered to be greatly reduced in the configuration with the shorter axis fore and aft. The flight tests indicated that a pitch control moment of 9.5 foot-pounds was more than adequate for trim at any of the speeds which could be attained with the power available. Apparently, there was an interference effect between the forward and rearward fans which strongly influenced the magnitude of the pitching moment. As the distance between the forward and rearward fans was reduced, the interference increased, which reduced the pitching moment. A qualitative analysis of this interference effect is presented in reference 2.

CONCLUSIONS

On the basis of free-flight tests of the stability and control characteristics of a model of an aerial vehicle supported by four lightly loaded ducted fans, the following conclusions are drawn:

1. Simple ducted-fan configurations similar to the test model are likely to have unstable oscillations in pitch and roll in hovering flight. The oscillation about an axis may be made easier to control by increasing the distance between ducts and may be stabilized completely by the addition of a sufficient amount of artificial damping.

2. The nose-down tilt angle and the pitch control required for trim in forward flight are each undesirably large.

3. Forward-flight requirements for nose-down tilt angle and pitch trim may be reduced by a cascade of vanes in the slipstream of the forward ducts, but the power penalty for such an installation may be high.

4. The pitch trim requirement in forward flight can also be reduced by reducing the fore-and-aft distance between the ducts, evidently because of increasing interference effects between the ducts.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., June 1, 1961.

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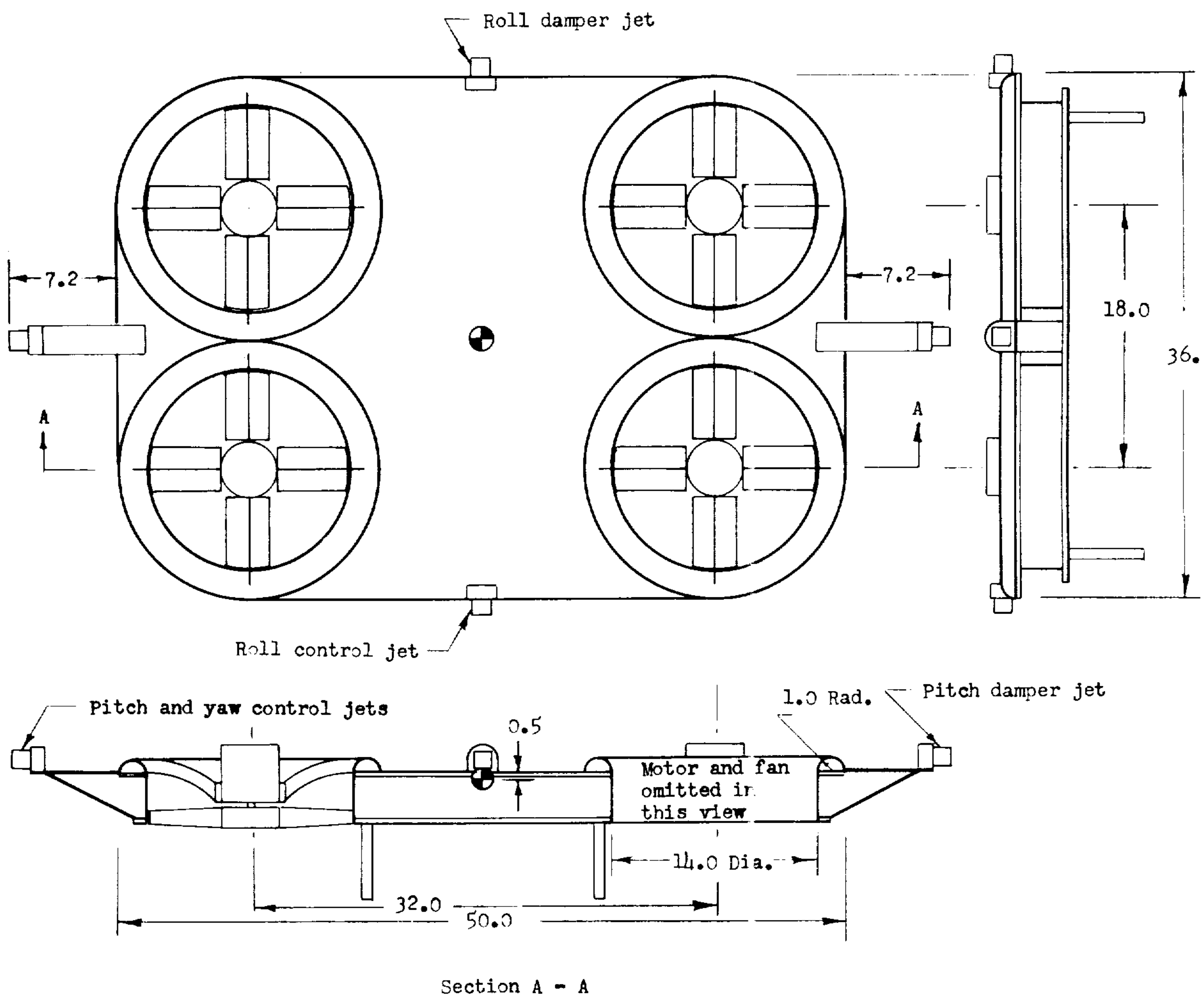
REFERENCES

1. McKinney, M. O.: Stability and Control of the Aerial Jeep. Preprint No. 10S, SAE Annual Meeting (Detroit, Mich.), Jan. 1959.

2. Parlett, Lysle P.: Wind-Tunnel Investigation of a Small-Scale Model of an Aerial Vehicle Supported by Ducted Fans. NASA TN D-377, 1960.

3. Parlett, Lysle P.: Stability and Control Characteristics of a Small-Scale Model of an Aerial Vehicle Supported by Two Ducted Fans. NASA TN D-920, 1961.



(a) Original configuration.

Figure 1.- Drawings of model. (All dimensions are in inches.)

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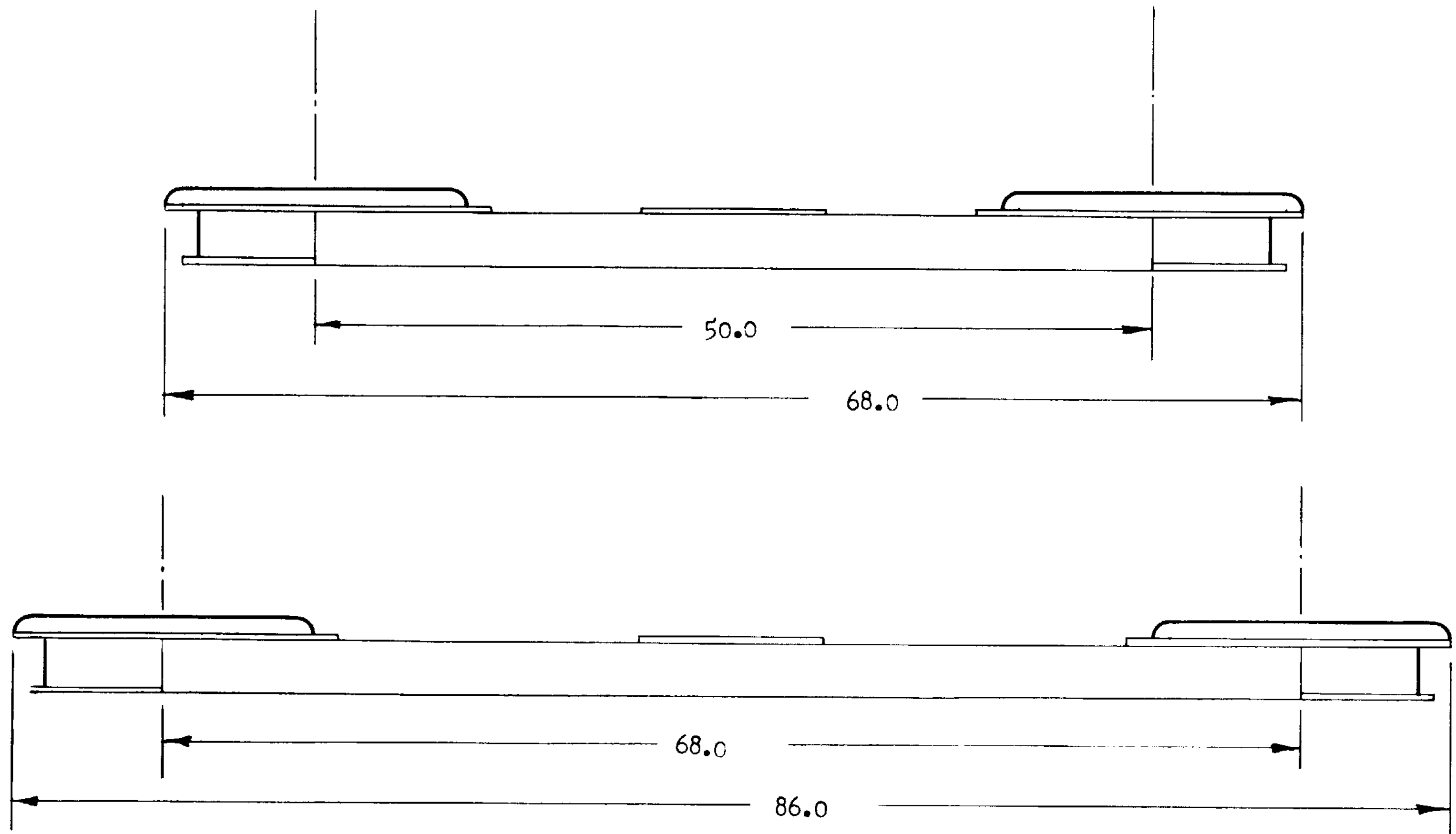
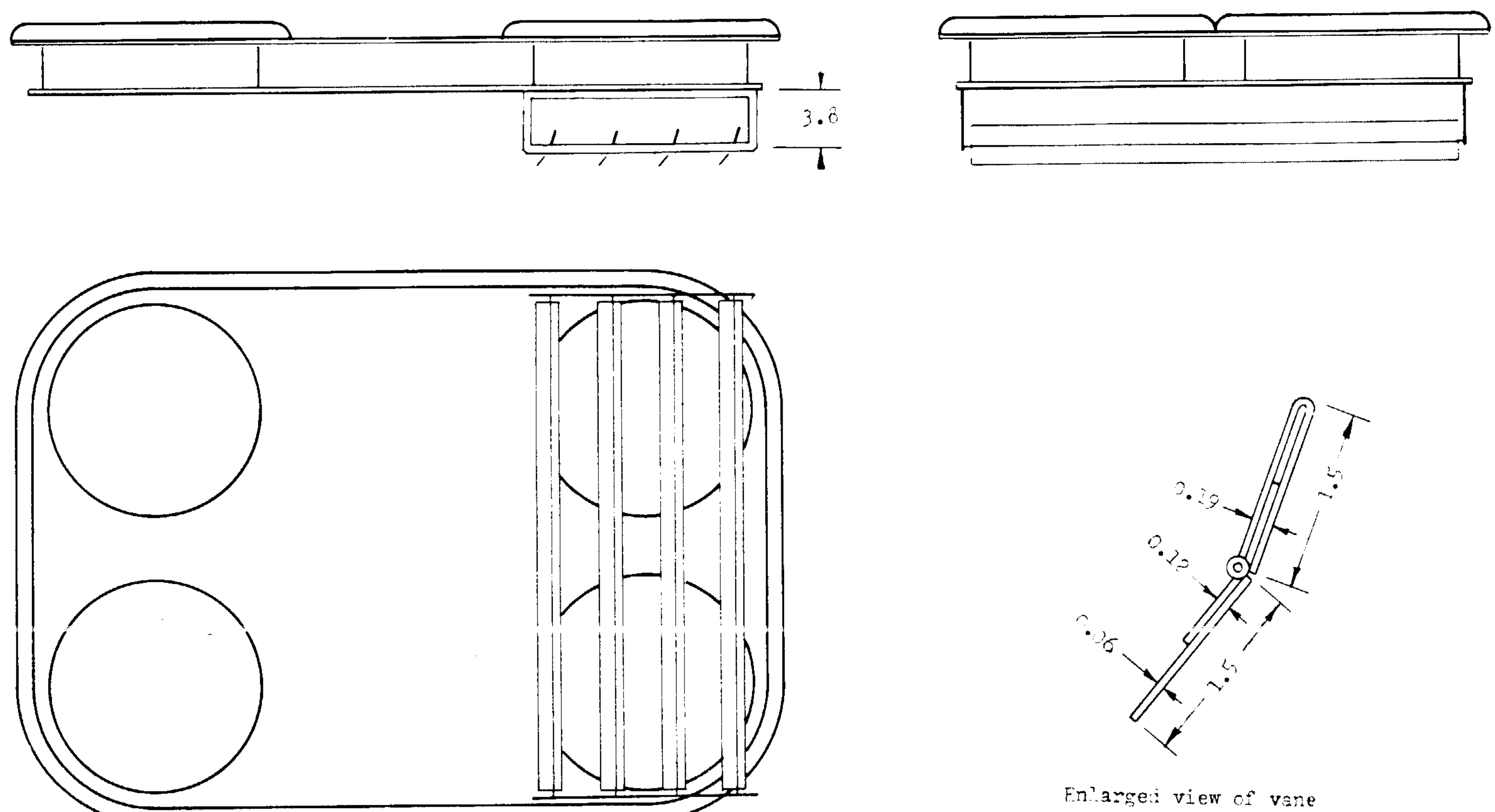


(b) Side view of model in two elongated configurations.

Figure 1.- Continued.



(c) Vane detail and installation.

Figure 1.- Concluded.

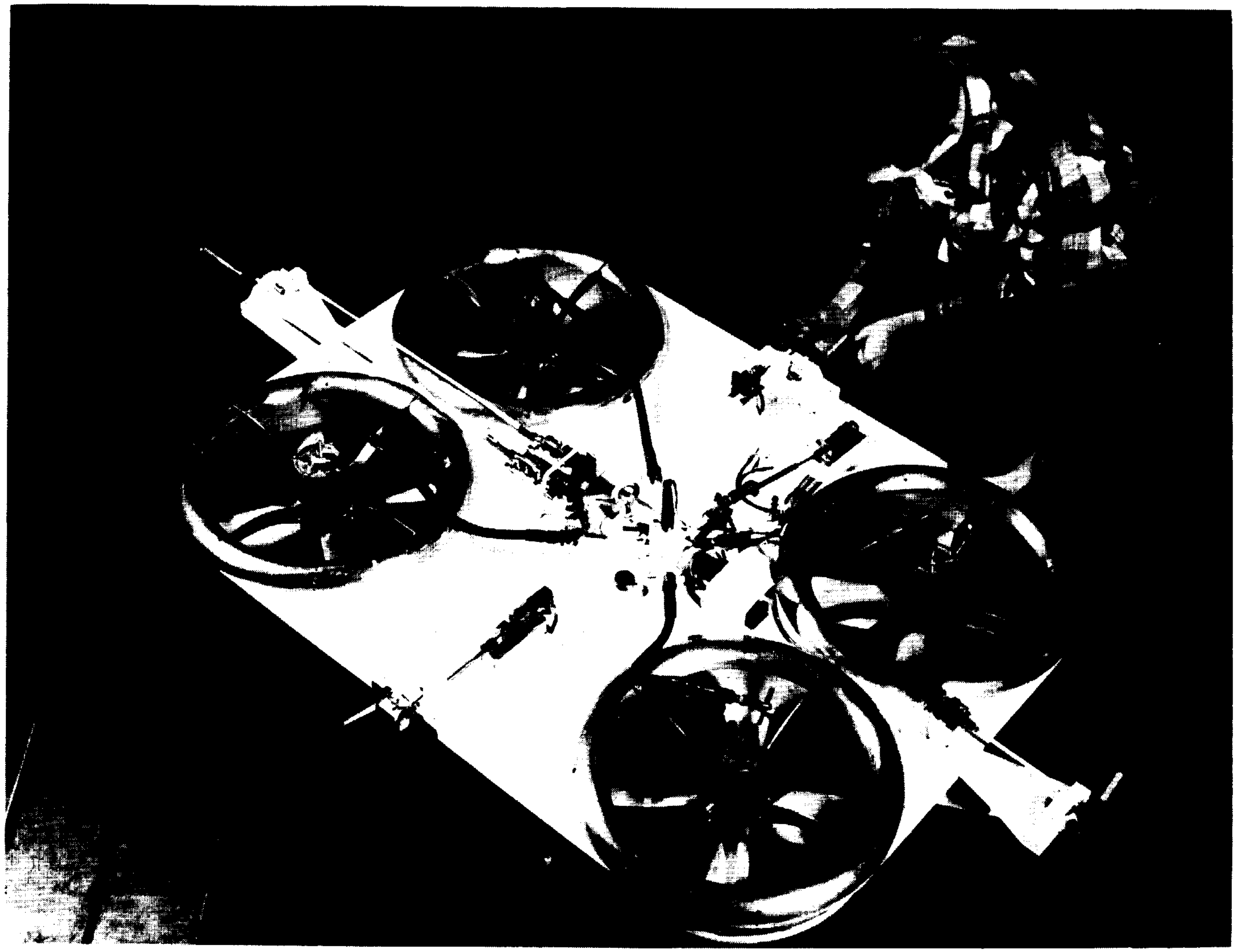


Figure 2.- Photograph of model in original configuration. L-58-432a

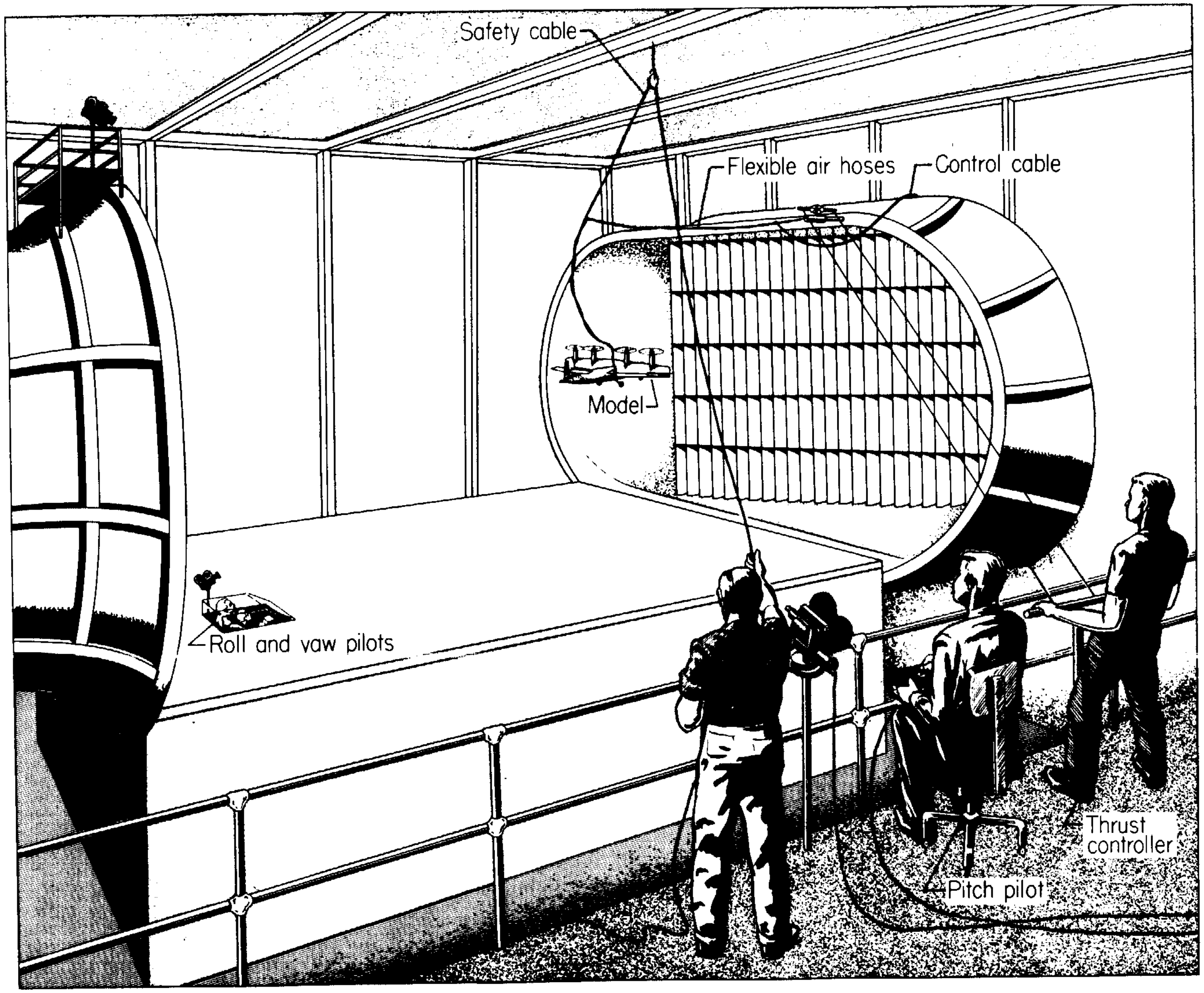


Figure 3.- Drawing of test setup in the Langley full-scale tunnel.

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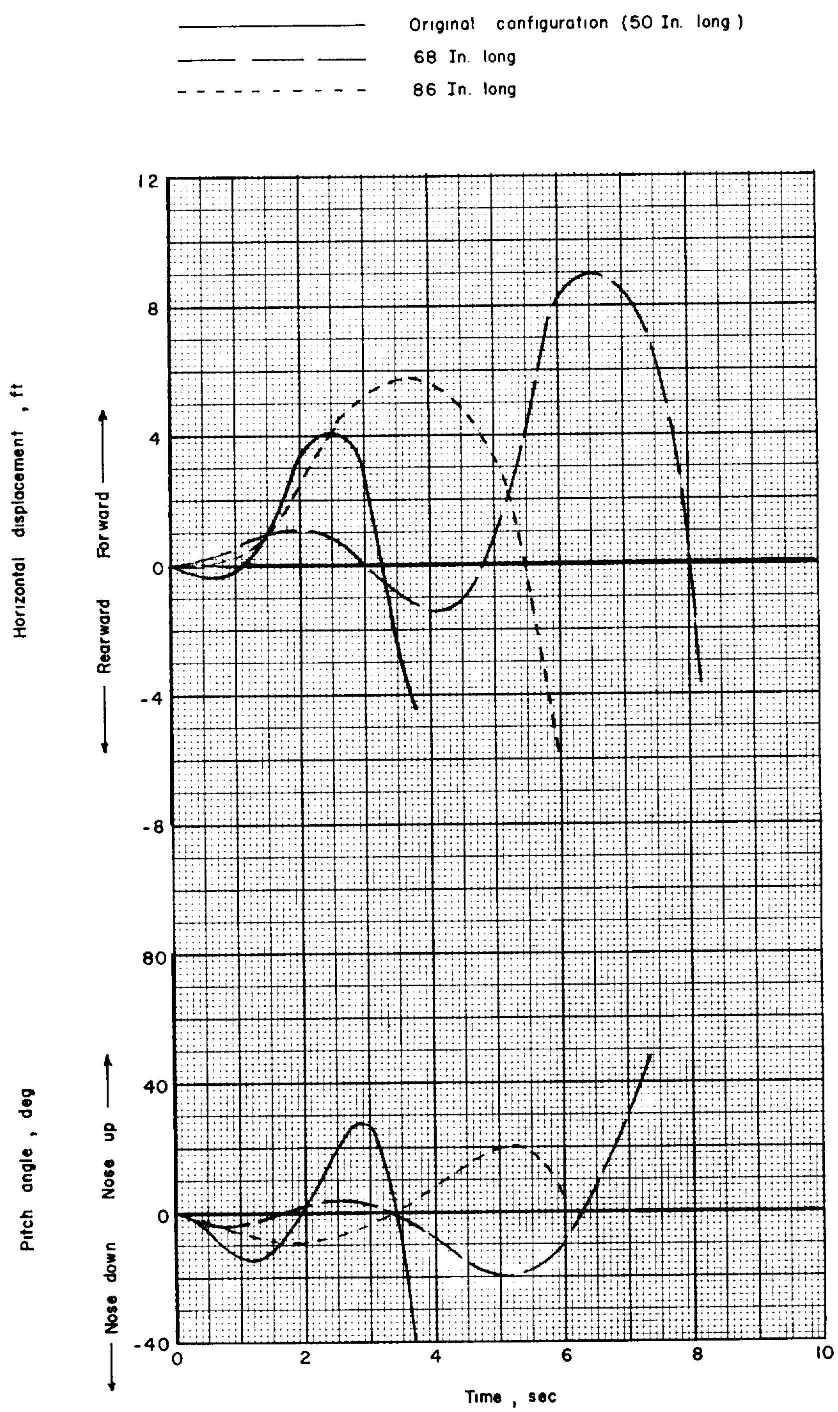

Figure 4.- Typical variation of pitch angle and horizontal displacement with time during uncontrolled longitudinal oscillations for three model lengths.

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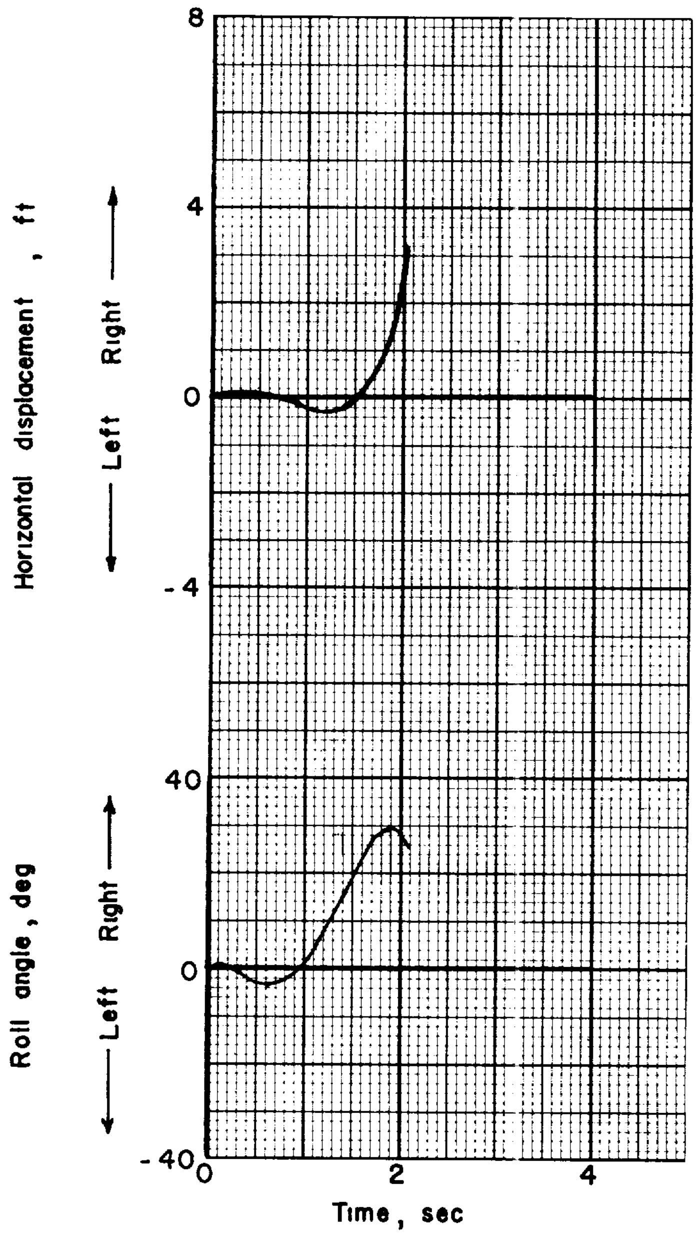

Figure 5.- Typical variation of roll angle and horizontal displacement with time during uncontrolled lateral oscillation.